

# Toward a more realistic holographic QCD model<sup>\*)</sup>

Mei HUANG<sup>1,2</sup>, Qi-shu YAN<sup>3</sup>, Yi YANG<sup>4</sup>

<sup>1</sup> *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*

<sup>2</sup> *Theoretical Physics Center for Science Facilities,  
Chinese Academy of Sciences, Beijing, China*

<sup>3</sup> *Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*

<sup>4</sup> *Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan*

By matching the  $Dp - Dq$  system in type II superstring theory with the Regge trajectories of vector and axial-vector meson spectra, a possible 5-dimension metric of a  $Dp - Dq$  soft-wall model has been determined. The dependence of the metric parameters on Regge trajectory parameters has been demonstrated. It is shown that the models defined in  $Dp$  brane background for  $p = 3$  or 4 can be consistent with experimental data.

## §1. Introduction

The discovery of the gravity/gauge duality<sup>2)</sup> has revived the hope to understand QCD in strongly coupled region using string theory. The gravity/gauge, or anti-de Sitter/conformal field theory (AdS/CFT) correspondence provides a revolutionary method to tackle the problem of strongly coupled gauge theories. For a review of AdS/CFT, see<sup>3)</sup>. The string description of realistic QCD has not been successfully formulated yet. Many efforts are invested in searching for such a realistic description by using the “top-down” approach, *i.e.* by deriving holographic QCD from string theory,<sup>4)</sup> as well as by using the “bottom-up” approach, *i.e.* by examining possible *holographic* QCD models from experimental data.<sup>5)–9)</sup>

It is an essential and crucial point for the realistic *holographic* QCD model to reproduce Regge behavior. Regge behavior is a well-known feature of QCD,<sup>10)</sup> and it was the commanding evidence for suggesting the string-like structure of hadrons. A general empirical expression for Regge trajectories can be cast as

$$M_{n,S}^2 = a_n n + a_S S + b, \quad (1.1)$$

where  $n$  and  $S$  are the quantum number of high radial and spin excitations, respectively. The slope  $a_n$  and  $a_S$  have dimension  $\text{GeV}^2$ , and describe the mass square increase rate in radial excitations and spin excitations, respectively. In principle,  $a_n$  is not necessarily the same as  $a_S$ , though  $a_n = a_S$  can be taken as a good approximation by fitting experimental data.<sup>11)</sup> The parameter  $b$  is the ground state mass square, and it is channel-dependent.

Currently, one of the most successful models derived from string theory is Sakai-Sugimoto model,<sup>12)</sup> which can describe spontaneously chiral symmetry breaking naturally, but fails to generate the linear Regge behavior. On the other hand, in the “bottom-up” approach, many efforts have been paid to generate the linear Regge

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<sup>\*)</sup> This talk is based on the paper<sup>1)</sup>.

behavior for meson spectra<sup>13)–15)</sup> and for baryon spectra.<sup>16)</sup> In Ref.,<sup>13)</sup> Karch, Katz, Son and Stephanov (KKSS) found that a  $z^2$  correction in the dilaton field leads to the linear behavior  $M_n^2 \propto n$ . In the KKSS model, which is also called soft-wall model, the background metric structure are assumed to have only the logarithmic term in the warp factor and the quadratic term in the dilaton field, the corresponding spectra for both vector and axial vector mesons are given as  $M_{n,S}^2 = 4n + 4S$ . Obviously, neither  $a_n$  nor  $a_S$  can be consistent with experimental data, where they should be close to one.<sup>11)</sup> Moreover, in this simple scenario, one cannot produce the ground state mass-square term  $b$ .

So a natural and important question is: what kind of *holographic* model can generate the realistic linear Regge behavior? We study this question by combining the “top-down” method and “bottom-up” method, *i.e.* by matching  $Dp - Dq$  system in type II superstring theory with the Regge trajectories of meson spectra in the hidden local symmetry model with group  $SU(2)_L \times SU(2)_R$ . We determine the possible structure of background metrics from the Regge trajectories of vector and axial-vector mesons. Our results show that the models defined in  $Dp$  brane background for  $p = 3$  or 4 can be consistent with experimental data quite well. These results may shed lights on the correct prescription of the string theory dual to the realistic QCD and can be useful to construct a correct phenomenological *holographic* model.

## §2. Regge trajectories of vector and axial-vector mesons

We will consider the chiral symmetry breaking  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$  by using the Higgsless model, the Hidden local symmetry version of chiral symmetry breaking. In this approach, the pseudo-scalar  $\pi$  is the zero mode of axial-vector field and there is no its radial and higher spin excitations. Then we only need consider  $S \geq 1$  mesons. We take as samples the data of the radial and spin excitations of  $\rho$  and  $a$  from PDG2007,<sup>17)</sup> which are listed in Table I. To describe Regge trajectories

n	1	2	3	4	5	6
$1_{\rho}^-$	0.770	1.450	1.700	1.900	2.150	2.270
$3_{\rho}^-$	1.690	1.990	2.250	—	—	—
$1_{a_1}^+$	1.260	1.640	1.930	2.095	2.270	2.340
$3_{a_3}^+$	1.870	2.070	2.310	—	—	—

Table I. Vector and axial-vector meson spectra (in GeV).

for both  $(\rho_1, \rho_3)$  and  $(a_1, a_3)$ , we use the general formula Eq. (1.1). From the experimental data, the parameters of Regge trajectories can be determined by using the standard  $\chi^2$  fit. The parameters for  $(\rho_1, \rho_3)$  mesons and their correlations read

$$\begin{aligned} a_n^\rho &= +0.91 \pm 0.23 \\ a_S^\rho &= +1.08 \pm 0.39 \\ b^\rho &= -1.09 \pm 1.18 \end{aligned} \begin{pmatrix} 1 & & \\ -0.82 & 1 & \\ +0.43 & -0.81 & 1 \end{pmatrix}. \quad (2.1)$$

The parameters for  $(a_1, a_3)$  mesons and their correlations read

$$\begin{aligned} a_n^a &= +0.81 \pm 0.22 \\ a_S^a &= +0.88 \pm 0.39 \\ b^a &= +0.13 \pm 1.17 \end{aligned} \begin{pmatrix} 1 & & \\ -0.82 & 1 & \\ +0.43 & -0.81 & 1 \end{pmatrix}. \quad (2.2)$$

It is known that chiral symmetry is spontaneously broken in the vacuum, thus the observed chiral partners are not degenerate. From the Regge trajectories of the chiral partners  $\rho$  and  $a$ , the chiral symmetry breaking in the vacuum is reflected by the difference of the ground state square-masses  $b^\rho$  and  $b^a$ . The difference is as large as  $1 \text{ GeV}^2$ , *i.e.*  $b^a - b^\rho \simeq M_{a_1}^2 - M_{\rho_1}^2 \simeq 1 \text{ GeV}^2$ .

### §3. Metric structure of $Dp - Dq$ system

In order to investigate the possible dual string theory for describing Regge behavior, we introduce the following  $Dp - Dq$  branes system in type II superstring theory. In the  $Dp - Dq$  system, the  $N_c$  background  $Dp$ -brane describe the effects of pure QCD theory, while the  $N_f$  probe  $Dq$ -brane is to accommodate the fundamental flavors which has been introduced by Karch and Katz.<sup>18)</sup> Such a practice is well motivated from string theory side. For example, in the Sakai-Sugimoto model,  $p = 4$  and  $q = 8$ . Low energy hadronic excitations are fields on probe  $Dq$  branes which is on the background determined by the background  $Dp$  branes.

First, we consider  $N_c$  background  $Dp$ -branes in type II superstring theory. The near horizon solution in 10-dimension space-time is<sup>19)</sup>

$$ds^2 = h^{-\frac{1}{2}} \eta_{\mu\nu} dx^\mu dx^\nu + h^{\frac{1}{2}} (du^2 + u^2 d\Omega_{8-p}^2), \quad (3.1)$$

where  $\mu, \nu = 0, \dots, p$ , the warp factor  $h(u) = (R/u)^{7-p}$  and  $R$  is a constant

$$R = \left[ 2^{5-p} \pi^{(5-p)/2} \Gamma\left(\frac{7-p}{2}\right) g_s N_c l_s^{7-p} \right]^{\frac{1}{7-p}}. \quad (3.2)$$

The coordinates transformation (for the cases of  $p \neq 5$ )  $u = \left(\frac{5-p}{2}\right)^{\frac{2}{p-5}} R^{\frac{p-7}{p-5}} z^{\frac{2}{p-5}}$  brings the above solution (3.1) to the following *Poincaré form*,

$$ds^2 = e^{2A(z)} \left[ \eta_{\mu\nu} dx^\mu dx^\nu + dz^2 + \frac{(p-5)^2}{4} z^2 d\Omega_{8-p}^2 \right]. \quad (3.3)$$

Consider  $N_f$  probe  $Dq$ -branes with  $q - 4$  of their dimensions in the  $S^{q-4}$  part of  $S^{8-p}$ , the induced  $q + 1$  dimensions metric on the probe branes is given as

$$ds^2 = e^{2A} \left[ \eta_{\mu\nu} dx^\mu dx^\nu + dz^2 + \frac{z^2}{z_0^2} d\Omega_{q-4}^2 \right]. \quad (3.4)$$

Where  $\mu, \nu = 0, \dots, 3$ , and the metric function of the warp factor only includes the logarithmic term

$$A(z) = -a_0 \ln z, \quad \text{with } a_0 = \frac{p-7}{2(p-5)}, \quad (3.5)$$

and the dilaton field part takes the form of

$$e^\Phi = g_s \left( \frac{2}{5-p} \frac{R}{z} \right)^{\frac{(p-3)(p-7)}{2(p-5)}}. \quad (3.6)$$

It follows that

$$\Phi(z) \sim d_0 \ln z, \text{ with } d_0 = -\frac{(p-3)(p-7)}{2(p-5)}. \quad (3.7)$$

The parameters  $a_0, d_0$  and other two parameters  $k, c_0$  used in Sec. 4 for any  $Dp - Dq$  system are listed in Table II.

$p$	3		4			6	
$q$	5	7	4	6	8	4	6
$k = -\frac{(p-3)(q-5)+4}{p-7}$	1		1	5/3	7/3	-1	-7
$a_0 = \frac{p-7}{2(p-5)}$	1		3/2			-1/2	
$c_0 = ka_0$	1		3/2	5/2	7/2	1/2	7/2
$d_0 = -\frac{(p-3)(p-7)}{2(p-5)}$	0		-3/2			3/2	

Table II. Theoretical results for the  $Dp - Dq$  system.

We notice that  $d_0 = 0$  for  $D3$  background branes, *i.e.* dilaton field is constant in  $\text{AdS}_5$  space. However, the dilaton field in a general  $Dp - Dq$  system can have a  $\ln z$  term contribution, e.g. in the  $D4 - D8$  system (Sakai-Sugimoto model<sup>12)</sup>),  $d_0 = -3/2$ .

#### §4. The deformed $Dp - Dq$ soft-wall model

In the above section, we have derived the general metric structure of the  $Dp - Dq$  system in Type II superstring theory, and we have noticed that the metric function  $A(z)$  only includes the logarithmic term, and in general there is another logarithmic contribution to the dilaton field. However, from the lessons of  $\text{AdS}_5$  metric ( $D3$  system) and the Sakai-Sugimoto model ( $D4 - D8$  system), the  $Dp - Dq$  system cannot describe linear trajectories of mesons. It was shown in Ref.<sup>13)</sup> in order to produce linear trajectories, there should be a  $z^2$  term, but all  $z^2$  asymptotics should be kept in the dilaton field  $\Phi(z)$  and not in the warp factor  $A(z)$ . Otherwise, the radial slope  $a_n$  will be spin dependent. Therefore, to describe the real QCD, we propose a deformed  $Dp - Dq$  soft-wall model which is defined as

$$A(z) = -a_0 \ln z, \quad \Phi(z) = d_0 \ln z + c_2 z^2. \quad (4.1)$$

By assuming that the gauge fields are independent of the internal space  $S^{q-4}$ , after integrating out  $S^{q-4}$ , up to the quadratic terms and following the same assumption as in<sup>13)</sup> we can have the effective 5D action for higher spin mesons described by tensor fields as

$$I = \frac{1}{2} \int d^5x \sqrt{g} e^{-\Phi(z)} \left\{ \Delta_N \phi_{M_1 \dots M_S} \Delta^N \phi^{M_1 \dots M_S} + m_5^2 \phi_{M_1 \dots M_S} \phi^{M_1 \dots M_S} \right\}, \quad (4.2)$$

where  $\phi_{M_1 \dots M_S}$  is the tensor field and  $M_i$  is the tensor index. The value of  $S$  is equal to the spin of the field. The parameter  $m_5^2$  is the 5D mass square of the bulk fields,  $g$  and  $\Phi(z)$  are the induced  $q+1$  dimension metric and dilaton field as shown in Eq. (3.4) and (3.7). The action for  $\rho_1, a_1$  and  $\rho_3, a_3$  mesons is given by taking  $S = 1$ , and  $S = 3$  respectively.

Following the standard procedure of dimensional reduction with mode decompositions  $\phi(x; z) = \sum_{n=0} \phi_n(x) \psi_n(z)$ , the equation of motion (EOM) of bulk wavefunctions  $\psi(z)_n$  for the general higher spin field can be derived as

$$\partial_z^2 \psi_n - \partial_z B \cdot \partial_z \psi_n + (M_{n,S}^2 - m_5^2 e^{2A}) \psi_n = 0, \quad (4.3)$$

where  $M_{n,S}$  is the mass of the 4-dimension field  $\phi_n(x)$  and

$$B = \Phi - k(2S - 1)A = \Phi + c_0(2S - 1)\ln z \quad (4.4)$$

is the linear combination of the metric background function and the dilaton field. It is worthy of remark that the spin parameter  $S$  enters in the factor  $B$  and can affect the EOM and spectra. The parameter  $k$  is a parameter depending on the induced metric (3.4) of the  $Dq$  brane. After integrating out  $S^{q-4}$ ,  $k$  is determined as  $k = -\frac{(p-3)(q-5)+4}{7-p}$ . It is obviously that  $k$  depends on both  $p$  and  $q$ . For simplicity, we have defined  $c_0 = ka_0 = -\frac{(p-3)(q-5)+4}{2(p-5)}$ . The combination function  $B(z)$  approaches logarithmic asymptotic at UV brane, and goes to  $z^2$  asymptotic at IR region.

The parameters  $c_0, d_0$  for any  $Dp - Dq$  system are listed in Table II. In the following, we hope to determine the possible realistic *holographic* QCD model from the Regge trajectories of vector and axial-vector mesons.

In the dictionary of AdS/CFT, a  $f$ -form operator with conformal dimension  $\Delta$  has 5-dimensional square-mass  $m_5^2 = (\Delta - f)(\Delta + f - 4)$  in the bulk,<sup>(20)</sup> and  $m_5^2 = 0$  for both vector and axial-vector mesons. In the formalism of DBI,  $m_5^2 = 0$  is also the consequence of gauge invariance. Thus we take  $m_{5,\rho}^2 = m_{5,a}^2 = 0$  in the following calculation. The spectra of EOM of Eq. (4.3) has an exact solution:

$$M_{n,S}^2 = 4c_2 n + 4c_2 c_0 S + 2c_2(1 - c_0 + d_0). \quad (4.5)$$

When  $c_0 = c_2 = 1$  and  $d_0 = 0$ , this solution reduces to results given in the Ref.<sup>(13)</sup> This exact solution strongly supports our parameterization on Regge trajectories and can tell how phenomenological parameters  $a_n, a_S$  and  $b$  are directly related with the metric parameters  $c_0, c_2$  and  $d_0$ . This solution shows that: 1)  $a_n$  is completely determined by  $c_2$ , *i.e.*  $c_2 = a_n/4$ ; 2)  $a_S$  is related with both  $c_0$  and  $c_2$ , and it is interesting to notice that  $c_0 = a_S/a_n$ , which indicates that  $c_0$  reflects the difference of string tension in the radial direction and spin direction; 3) The ground state square-mass  $b$  is related with all metric parameters, and  $d_0$  can be solved out as  $d_0 = \frac{2b}{a_n} + \frac{a_S}{a_n} - 1$ .

If we take the approximation of  $a_n = a_S = 1$ , we have  $c_0 = 1, c_2 = 1/4$  for both vector and axial-vector mesons, while  $d_0$  is mainly determined by the ground state square-mass as  $d_0^{\rho/a} = 2b^{\rho/a}$ .

We use Eq. (4.5) to fit the spectra of vector and axial-vector mesons. The central values and correlation matrix for vector mesons read as

$$\begin{aligned} c_0^\rho &= +1.19^{+0.45}_{-0.39} \\ c_2^\rho &= +0.23^{+0.06}_{-0.06} \\ d_0^\rho &= -2.24^{+2.53}_{-1.68} \end{aligned} \begin{pmatrix} 1 & & \\ -0.39 & 1 & \\ +0.02 & -0.89 & 1 \end{pmatrix}, \quad (4.6)$$

while the central values and correlation matrix for axial-vector mesons read as

$$\begin{aligned} c_0^a &= +1.09^{+0.50}_{-0.44} \\ c_2^a &= +0.20^{+0.06}_{-0.06} \\ d_0^a &= +0.51^{+3.98}_{-2.36} \end{aligned} \begin{pmatrix} 1 & & \\ -0.43 & 1 & \\ +0.25 & -0.97 & 1 \end{pmatrix}. \quad (4.7)$$

Since these two individual fitting suggest it is possible to use a common metric (  $c_0$  and  $c_2$  ) to describe radial and higher spin excitations of both  $\rho$  and  $a_1$  mesons, we can fit the data in Table I with four theoretical free parameters  $c_0$ ,  $c_2$ ,  $d_0^\rho$ , and  $d_0^a$ , which read as

$$\begin{aligned} c_0 &= +1.19^{+0.54}_{-0.54} \\ c_2 &= +0.20^{+0.06}_{-0.08} \\ d_0^\rho &= -2.24^{+4.51}_{-1.72} \\ d_0^a &= +0.00^{+4.20}_{-2.83} \end{aligned} \begin{pmatrix} 1 & & & \\ -0.93 & 1 & & \\ +0.88 & -0.98 & 1 & \\ +0.90 & -0.99 & +0.98 & 1 \end{pmatrix}. \quad (4.8)$$

The result shows that it is possible to economically accommodate Regge trajectories of both  $\rho$  and  $a_1$  with just 3 nonvanishing parameters ( $c_0$ ,  $c_2$ , and  $d_0^\rho$ ). Our fitting results show that  $c_0$  prefers to the value of  $1 \sim 1.5$ , compared with table II (For  $D_3 - Dq$  background brane case, both  $q = 5$  and  $q = 7$  probe brane cases correspond to  $c_0 = 1$ , which is within the allowed overlapping region; for  $D4$  background brane case, only  $q = 4$  case corresponds to  $c_0 = 1.5$  which is within the allowed overlapping region; for  $D6$  background brane case, no  $Dq$  probe brane case can be allowed in the allowed overlapping region.), this indicates that the *holographic* QCD model should be close to models defined in  $Dp$ -branes background for  $p = 3$  or 4.

## §5. Discussions and conclusion

**Discussion on  $d_0$ :** In order to understand more about the logarithmic term in the dilaton field, *i.e.*  $d_0 \ln z$ , it should be helpful to compare our holographic model with an extended KKSS model, which only includes logarithmic term in  $A(z)$  and only  $z^2$  term in the dilaton field. The extended KKSS model has the form of

$$A(z) = -a_0 \ln z, \quad \Phi(z) = c_2 z^2. \quad (5.1)$$

By using the central values of Eqs. (2.1-2.2) and using the shooting method to find spectra from EOM and boundary conditions, we determine the best value of  $c_0$ ,  $c_2$  and  $m_5^2$  for radial and spin meson excitations, respectively. The best fitted values of ( $c_0^\rho, c_2^\rho, m_{5,\rho}^2$ ) and ( $c_0^a, c_2^a, m_{5,a}^2$ ) are found to be

$$\begin{aligned} c_0^\rho &= 1.28, & c_0^a &= 1.50, \\ c_2^\rho &= 0.21 \text{ GeV}^2, & c_2^a &= 0.19 \text{ GeV}^2, \\ m_{5,\rho}^2 &= -0.06 \text{ GeV}^2, & m_{5,a}^2 &= 1.11 \text{ GeV}^2. \end{aligned} \quad (5.2)$$

In our fitting, we have taken the 5D mass as a free constant not a  $z$  dependent function as treated in Refs.<sup>13),16)</sup> It is noticed that the 5D square-mass for vector mesons is almost zero, and is around  $1\text{GeV}^2$  for axial-vector mesons, which is a direct consequence of the chiral symmetry breaking  $SU(2)_L \times SU(2)_R \rightarrow SU(2)_D$ . This is similar to the case in Ref.<sup>13)</sup> where 5D mass for  $\rho$  is zero, and the axial-vector meson picks up a finite 5D mass via the Higgs mechanism from the background scalar field. It is found that by using the extended KKSS model, in order to fit the vacuum square mass of Regge trajectories, different nonzero 5D square-mass is required for vector and axial vector meson, respectively. It is suggested that  $d_0^{\rho/a} \ln z$  contribution in the dilaton field in our holographic model proposed in Sec. IV plays the same role as the  $m_{5,\rho/a}^2$  in the extended KKSS scenario model, which might indicate that the chiral symmetry breaking is encoded in the logarithmic term of the dilaton background.

**Discussion on  $c_2$ :** It is found that  $c_2$  is not sensitive to  $Dp - Dq$  system, and mainly determined by the value of string tension or the slope of the radial excitations via the relation  $c_2 = a_n/4$ . 1) In,<sup>13)</sup>  $c_2$  was simply taken as  $1\text{GeV}^2$ . 2) in the back reaction holographic dual model,<sup>21)</sup>  $c_2$  is determined as  $m_q^2/24$  ( $m_q$  the quark mass). For both cases, the  $c_2$  cannot accommodate experimental data. Andreev in Ref.<sup>22)</sup> shows that there is an upper bound of  $c_2$ .  $c_2$  can be determined by the coefficient  $C_2$ <sup>23)</sup> of the quadratic correction to the vector-vector current correlator<sup>24)</sup>

$$\mathcal{N}q^2 \frac{d\Pi_V}{dq^2} = C_0 + \frac{1}{q^2}C_2 + \sum_{n \geq 2} \frac{n}{q^{2n}}C_{2n}\langle \mathcal{O}_{2n} \rangle, \quad (5.3)$$

where  $C_2$  can be determined from  $e^+e^-$  scattering data.<sup>25)</sup> According to,<sup>22)</sup> the relation between  $C_2$  in Eq. (5.3) and the parameter  $c_2$  for Dilaton field is:  $c_2 = -\frac{3}{2}C_2$ . The experimental bound  $|C_2| \leq 0.14\text{GeV}^2$  gives  $|c_2| \leq 0.21\text{GeV}^2$ . Our fitting results of  $c_2$  is around 0.2 and is within the experimental upper bounds.

In summary, the parameters of metric structure of the holographic QCD model is determined by matching  $Dp - Dq$  soft-wall model in type II superstring theory with the Regge trajectories parameters of vector and axial-vector mesons spectra. Our results show that the models defined in  $Dp$  brane background for  $p = 3$  or 4 can be consistent with experimental data. According to the study of the reference,<sup>11)</sup> the parameters  $a_n$  and  $a_s$  is almost universal for all mesons spectra due to their common strong interaction origin ( the subtle differences in  $a_n$  and  $a_s$  for different mesons can be attributed to higher order effects or other dynamics like the chiral symmetry breaking ). Although we have only used data of radial and higher spin excitations of  $\rho$  and  $a_1$  mesons, the equation of motion of KK modes is universal to mesons with different CP charges, our conclusion should also be valid for other types of mesons. We also show the dependence of the metric parameters on the Regge trajectories parameters: The quadratic term in the dilaton background field is solely determined by the slope in the radial direction; The warp factor is mainly determined by the difference of the slope in the spin direction and the radial direction; In order to produce the ground state square-masses, it is required to have different finite 5D square-mass or equivalently different logarithmic terms in the dilaton field for vector and axial-vector mesons, which encodes the information of the chiral symmetry breaking. This

information is important for the construction of a realistic holographic QCD model. Once the universal background metric and meson-dependent parameters are determined from mass spectra are determined from mass spectra, we can further test the  $D_p - D_q$  soft-wall model by calculating cross sections, decay widths, branching ratios, etc, of mesons.

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